

Rotational Head Acceleration Measurement Techniques and Headform Characteristics: Implication on Helmet Impact Testing

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ABSTRACT

Evaluating the impact performance of helmets in the laboratory presents challenges. The experimental setup must be able to accurately model helmet fit on a headform, reliably measure head kinematics resulting from impact, and produce a biofidelic head impact response. This study investigates these factors and discusses the implications of the results on laboratory helmet testing procedures. The objectives of this study are to quantify differences in shape between Hybrid III and NOCSAE headforms, and to compare rotational kinematic measurement techniques using accelerometer arrays and angular rates sensors. Headform shape was compared between the 50th percentile Hybrid III and medium NOCSAE headforms. Both headforms were scanned using a coordinate measuring machine equipped with a laser line probe (FARO Arm) to generate a 3-D point cloud characterizing surface geometry. The headforms were aligned by minimizing the sum of square differences between the headform surface contours. Maximum differences and root mean square deviations between the headforms were quantified over the entire 3-D surface, the mid-sagittal plane, and 3 coronal cross-sections. From the base of skull to the brow, the two headforms are nearly identical. However, substantial differences exist between the jaw, cheek, and where the nape of the neck meets the skull. These characteristics can have a profound effect on helmet fit and suggest that the NOCSAE headform may be more appropriate for helmet testing. Unfortunately, the NOCSAE headform was designed with the intention of only recording linear acceleration, and not the rotational kinematics resulting from impact. Recently, six degree of freedom (6DOF) instrumentation packages consisting of 3 linear accelerometers and 3 angular rate sensors have become available that are small enough to fit into the instrumentation channel of the NOCSAE headform. The efficacy of using these 6DOF instrumentation packages was investigated through helmeted impact testing with the Hybrid III headform using a linear impactor. The Hybrid III headform was simultaneously instrumented with a 3-2-2-2 accelerometer array and the 6DOF instrumentation package. A total of 18 tests consisting of 6 impact locations and 3 impact energies were conducted. Rotational accelerations were calculated from the 3-2-2-2 array and the angular rate sensors.

Filtering of the angular rate data was optimized to match the rotational accelerations calculated from the 3-2-2-2 array. With an optimal CFC 155 J211 filter, the angular rate data deviated from the 3-2-2-2 data by an average of $0.3\% \pm 5.2\%$. Root mean square error was quantified to be 218 rad/s². Overall, there was good agreement between the 2 methods of calculating rotational acceleration. Future work should compare the inertial properties and impact response of the Hybrid III and NOCSAE headforms.

INTRODUCTION

Evaluating the impact performance of helmets in the laboratory presents challenges. The experimental setup must be able to accurately model helmet fit on a headform, reliably measure head kinematics resulting from impact, and produce a biofidelic head impact response. Geometric and inertial differences between existing headforms can lead to performance differences between helmets. Furthermore, both linear and rotational acceleration of the head contribute to risk of brain injury. Understanding these accelerations to impact loading events is critical to improving the performance of protective devices, such as helmets. Unfortunately, measuring rotational acceleration of the head presents challenges. While a nine accelerometer array in a 3-2-2-2 configuration is considered the ‘gold standard,’ it is not always possible to instrument headforms with this array. Angular rate sensors are an alternative, but provide inherently noisier data than accelerometers that must be differentiated. This study investigates these factors and discusses the implications of the results on laboratory helmet testing procedures. The objectives of this study are to quantify differences in shape between Hybrid III and NOCSAE headforms, and to compare rotational kinematic measurement techniques using accelerometer arrays and angular rates sensors.

METHODS

Headform Shape Analysis

Shape comparisons were made between the 50th percentile Hybrid III and medium NOCSAE headforms. Measurements were taken of the two headforms using a coordinate measuring machine equipped with a Laser ScanArm (FARO Arm). Excess data points were removed and surfaces smoothed in post-processing using Geomagic Studio 2012 software. A program was written in MATLAB to import the 3D point cloud data and align the headforms to a common coordinate system for comparisons. The mid-sagittal plane of each headform was found by comparing symmetry across the mid-lines of three coronal plane cross-sections located anterior to, posterior to, and at the CG of the headform. Locations in each coronal cross-section were defined by a polar coordinate system (θ) and divided into 1° increments from -90° to 90° with the 0° line at the top of the headform, separating the left and right sides. The root-sum-square (RSS) of differences between corresponding radii (r) on either side of the midline were determined for each coronal plane as roll (lateral neck flexion) and yaw (head rotation about the long axis of the body) of the head were varied to find the minimum RSS value (Eq. 1). The subscript i corresponds to each angle θ .

$$RSS_{L-R} = \sqrt{\sum_i (r_R(\theta_i) - r_L(-\theta_i))^2} \quad (1)$$

The Hybrid III and NOCSAE headforms were then aligned to one another using the same coronal planes, this time comparing the radii between the two rather than the left and right sides of the same headform (Eq. 2). The pitch angle (neck flexion/extension) and position in the mid-sagittal plan of the NOCSAE headform were varied to optimally align the headforms.

$$RSS_{HIII-NOCSAE} = \sqrt{\sum_i (r_{HIII}(\theta_i) - r_{NOCSAE}(\theta_i))^2} \quad (2)$$

Cross-sectional comparisons were made between the two headforms in the mid-sagittal and three coronal plans. In the mid-sagittal plan, the polar coordinate system ranged from -180° to 180° with 0° at the back of the head. The coronal planes were positioned based on measurements from the CG of the Hybrid III, with one 38.1 mm anterior, another 63.5 mm posterior, and the other at the CG. For all three coronal plans, the polar coordinate system ranged from -180° to 180° with 0° at the top of the head.

Comparisons were made using two metrics: root-mean-square radial deviation (RMSD) and maximum radial deviation (MRD) (Eqs. 3 and 4). The N in Eq. 3 is the total number of points compared. The ranges used for comparisons were selected to represent regions of the head likely to affect helmet fit.

$$RMS = \sqrt{\frac{1}{N} \sum_i (r_{HIII}(\theta_i) - r_{NOCSAE}(\theta_i))^2} \quad (3)$$

$$MRD = (r_{HIII}(\theta_i) - r_{NOCSAE}(\theta_i))_{max} \quad (4)$$

Rotational Acceleration Measurement

Laboratory testing was conducted to determine the efficacy of using angular rate sensors to measure the head kinematics resulting from impact. This was accomplished by simultaneously instrumenting a Hybrid III dummy headform with a 3-2-2-2 nine accelerometer array and 3 angular rate sensors. The Hybrid III headform was equipped with a helmet and impacted at a range of impact energies and locations. The angular rate data were compared to the 3-2-2-2 nine accelerometer array measurements.

A pneumatic linear impactor was used to simulate helmet-to-helmet impacts experienced by football players (Pellman et al., 2006). The 14.5 kg impactor ram was equipped with an impacting surface designed to replicate the impacting characteristics of a typical helmet. An instrumented Hybrid III 50th percentile male headform and neck were mounted on a linear slide table that consisted of a sliding mass representative of the effective mass of a torso. The headform was equipped with a Large Riddell Revolution Speed helmet. A skull cap was also fitted to the headform to reduce the friction between the Hybrid III skin and helmet.

A total of 18 tests were performed. Six impact locations on the helmet were tested, which included centric and non-centric impacts to the helmet shell and facemask. Impact locations chosen were based on previous research that identified helmet impact locations commonly associated with concussion in professional football players (Pellman et al., 2003). Each impact location was tested at 3 impact velocities (4.8, 7.2, and 9.5 m/s) representative of moderate to high energy impacts in football (Pellman et al., 2003). Impact velocity was measured for each test with a dual beam light gate that the impactor would pass through just before impact on each test.

The Hybrid III dummy headform was instrumented with a 3-2-2-2 accelerometer array and 3 angular rate sensors. The center of gravity of headform was instrumented with a 6 degree of freedom sensor package consisting of 3 linear accelerometers and 3 angular rate sensors (6DX PRO 2K-18K, Diversified Technical Systems, Seal Beach, CA). An additional 6 accelerometers (7264-2000B, Endevco, San Juan Capistrano, CA) were mounted to the interior surface of the skull of the headform. All data were collected at 20 kHz. For each test, resultant rotational head acceleration was calculated from the 3-2-2-2 accelerometer array and the angular rate sensor data. All accelerometer data were filtered to channel frequency class (CFC) 180 to minimize the effects of spurious noise in the 3-2-2-2 calculations (Newman et al., 2005).

To evaluate the angular rate sensor's ability to determine rotational accelerations, the filtering of the angular rate data was optimized to best match peak resultant rotational accelerations measured by the 3-2-2-2 accelerometer array. Angular rate data were filtered with CFC values ranging from 5 Hz to 1000 Hz in increments of 5 Hz. Data were then differentiated and resultant rotational acceleration was determined. Root mean square (RMS) error of peak resultant rotational acceleration for the 18 tests was computed at each CFC value. The CFC value that minimized RMS error was selected as the best method to filter these data. In addition to RMS error, average errors were computed. A linear regression analysis that used a least squares technique with a zero constraint was performed to evaluate the correlation between the 3-2-2-2 accelerometer array and angular rate sensor measurement methods.

RESULTS

Headform Shape Analysis

Planar comparisons revealed only small differences in the upper portions of the Hybrid III and NOCSAE headforms, though larger differences were apparent in other regions. The MRDs in the upper regions of the two headforms ranged from 2.1 mm in the mid-sagittal plane to 3.5 mm in the anterior coronal plane (Figures 1 and 2). The RMS values across the four planes ranged from 1.1 mm in the mid-sagittal plane to 1.7 mm in the anterior coronal plane. Larger differences were observed at the base of the skull in the mid-sagittal and posterior coronal plane as well as the jaw and cheek bone regions of the anterior and mid-coronal planes. Differences at the base of the skull were too large to warrant radial comparisons. In the jaw and cheek bone regions, the largest differences were noted in the anterior-coronal plane, where the MRD was 7.6 mm and the RMS was 4.2 mm.

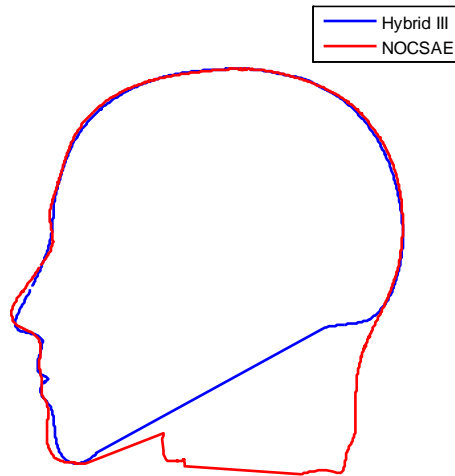


Figure 1: Comparison of headform shape in the mid-sagittal plane for the Hybrid III (blue) and NOSAE (red) headforms. The upper skull contours are very similar, but the contours diverge at the base of the neck. Furthermore, the NOCSAE headform has a more pronounced chin.

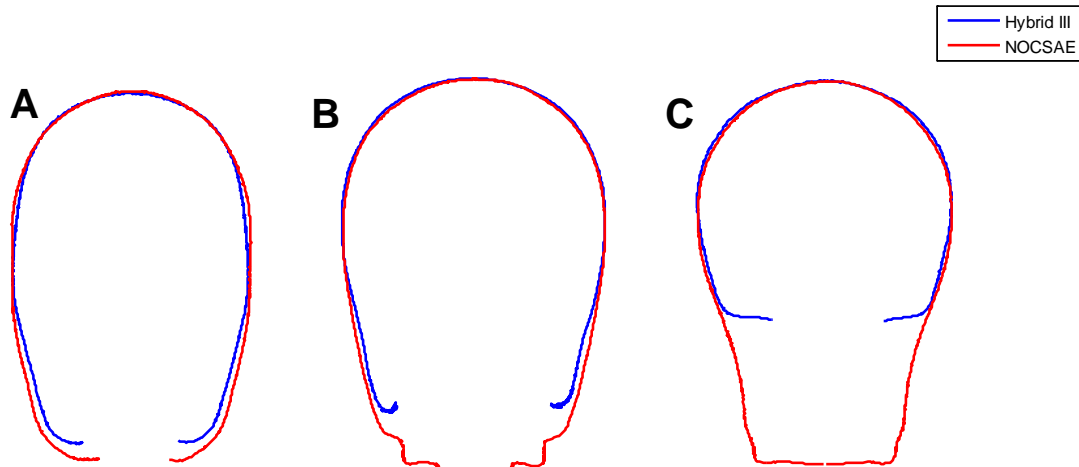


Figure 2: Planar comparisons of the Hybrid III (blue) and NOCSAE (red) headforms in the anterior-coronal (A), mid-coronal (B), and posterior-coronal planes (C). The upper skull contours are very similar, but the contours diverge at the jaw, cheeks, and base of the neck.

Rotational Acceleration Measurement

RMS error between peak rotational acceleration determined from the angular rate sensor was minimized when the filter had a CFC value of 155 Hz (Figure 3). When filtering the angular rate data at CFC 155, RMS error for peak rotational acceleration was 218 rad/s^2 . RMS error was below 500 rad/s^2 from CFC 90 to 270, and below 300 rad/s^2 from CFC 120 to 205. Average error for rotational accelerations determined from angular rate data filtered at CFC 155 was $-4 \text{ rad/s}^2 \pm 224 \text{ rad/s}^2$. When normalizing rotational acceleration errors to rotational accelerations determined from the nine accelerometer array, average error was $0.27\% \pm 5.2\%$. There was a strong, linear correlation (Figure 4) between the two methods for computing rotational head acceleration ($R^2 = 0.99$).

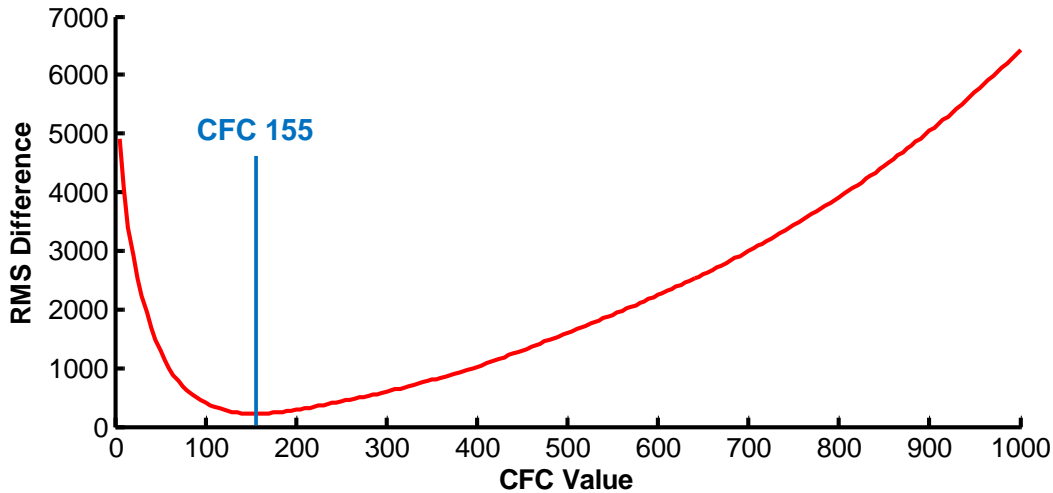


Figure 3: A CFC value of 155 Hz minimized the RMS error between peak rotational accelerations determined from the angular rate sensor and nine accelerometer array

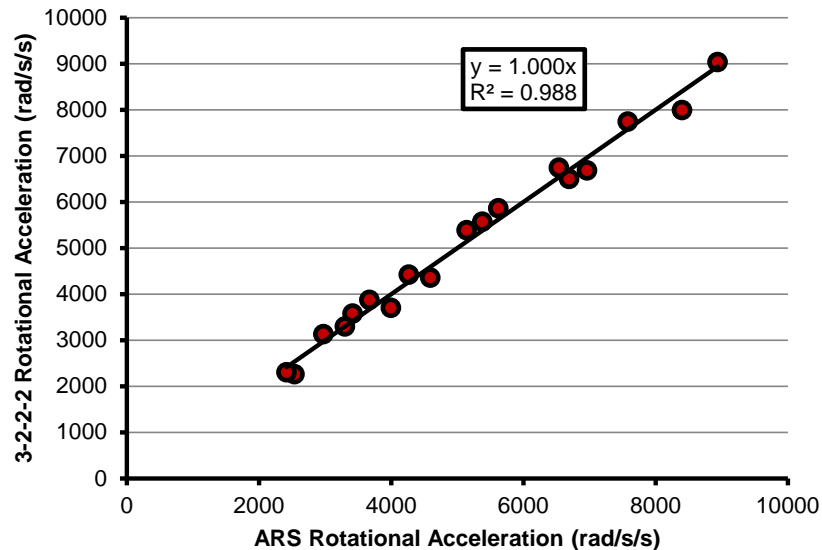


Figure 4: Rotational accelerations computed from the 3-2-2 array and angular rate sensor were highly and linearly correlated throughout the range of impact conditions tested.

CONCLUSIONS

While the upper skulls of the headforms were nearly identical, large differences were found at the base of the skull, cheeks, and jaw. These differences affect helmet fit and allow greater helmet rotation relative to the Hybrid III headform. While the effect of fit on helmet performance has yet to be quantified, it is important for the helmet fit to be realistic as manufacturers will design helmets to perform well in the laboratory. Future work should quantify the effect of helmet fit and compare the inertial properties and biomechanical impact responses of the headforms. Furthermore, angular rate sensors appear to be a feasible alternative to the standard 3-2-2-2 accelerometer array. However, applying the appropriate filter to the angular rate data is critical for accurately quantifying rotational head acceleration. For helmeted head impacts, a CFC value of 155 was determined to best match rotational accelerations calculated from the 3-2-2-2 array. Future work should investigate the repeatability of these two measurement methods to assess potential sources of variance.

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